Space Charge Effect at ProtoDUNE

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BNL

BNL DUNE Meeting

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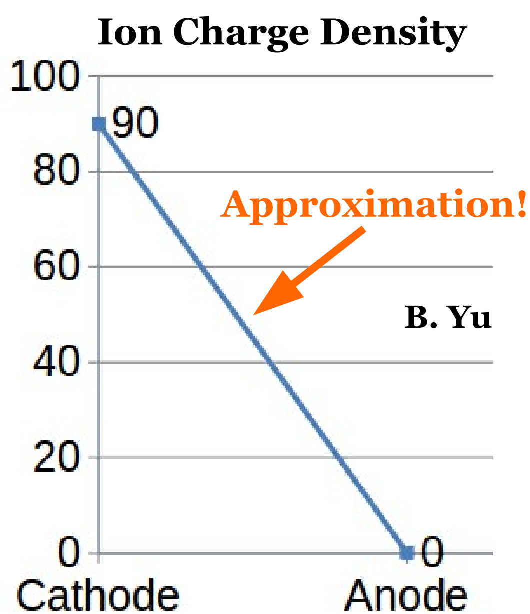
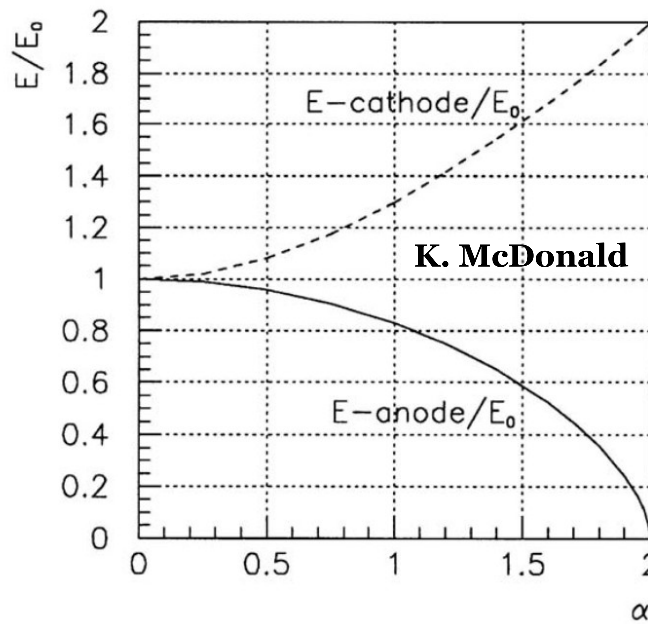
Introduction

- Tool exists to study space charge effect at the **MicroBooNE detector**
  - **SpaCE** – Space Charge Estimator
  - Study **simple problems** first in detail with dedicated simulations
  - Also performs calibration using MicroBooNE's UV laser system and cosmic muons (in progress)
  - LArSoft module exists to hold/access SCE offsets (undergoing modification for generic LArTPC experiment)
  - Now: extend SCE simulation to **ProtoDUNE**
- Outline:
  - Brief review of Space Charge Effect (SCE) and SpaCE
  - Impact of SCE on track reconstruction
  - SCE at ProtoDUNE

Space Charge Effect

- **Space charge**: excess electric **charge** (slow-moving ions) distributed over region of **space** due to cosmic muons passing through the liquid argon
  - Modifies E field in TPC, thus track/shower reconstruction
  - Effect scales with L^3, $E^{-1.7}$





$$\alpha = \frac{D}{E_0}\sqrt{\frac{K}{\epsilon\mu}}$$

$$\mathbf{v} = \mu \mathbf{E}$$

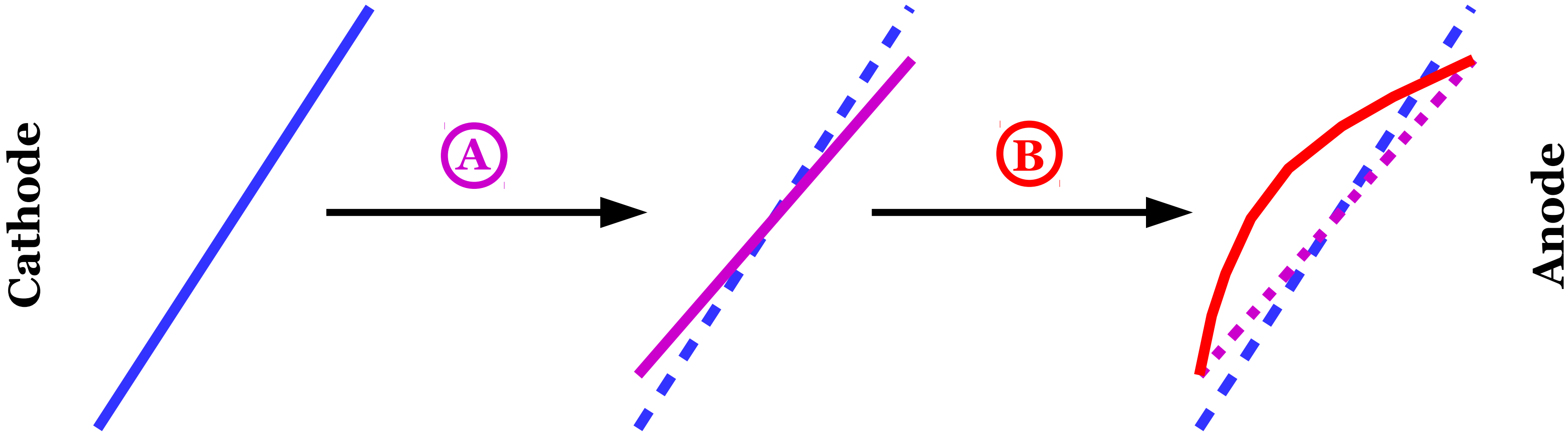
No Drift!

SpaCE: Overview

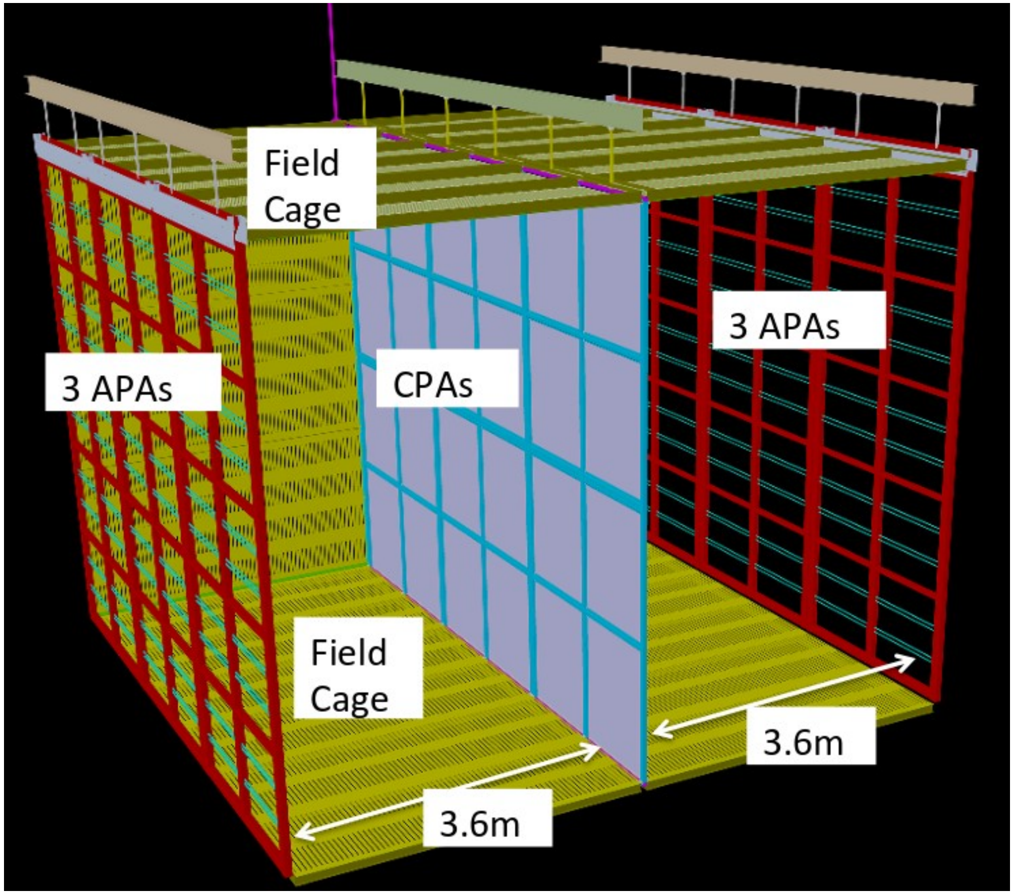
- Code written in C++ with ROOT libraries
- Also makes use of external libraries (ALGLIB)
- Primary features:
  - Obtain E fields analytically (on 3D grid) via **Fourier series**
  - Use **interpolation** scheme (RBF – radial basis functions) to obtain E fields in between solution points on grid
  - Generate tracks in volume – line of uniformly-spaced points
  - Employ **ray-tracing** to "read out" reconstructed {x,y,z} point for each track point – RKF45 method
- First implemented effects of uniform space charge deposition without liquid argon flow (only linear space charge density)
  - Also can use **arbitrary space charge configuration**
    - Can model effects of liquid argon flow (however, interpretation is difficult)

Impact on Track Reco.

- Two separate effects on reconstructed **tracks**:
  - A • Reconstructed track shortens laterally (looks rotated)
  - B • Reconstructed track bows toward cathode (greater effect near center of detector)
- Can obtain straight track (or multiple-scattering track) by applying corrections derived from data-driven calibration



Nominal Geometry



- Nominal ProtoDUNE geometry:
  - Drift (X): 3.6 m
  - Height (Y): 5.9 m
  - Length (Z): 7.0 m
- Dimensions used for simulations slightly different (to simplify calculations):
  - Drift (X): 3.6 m
  - Height (Y): 6.0 m
  - Length (Z): 7.2 m

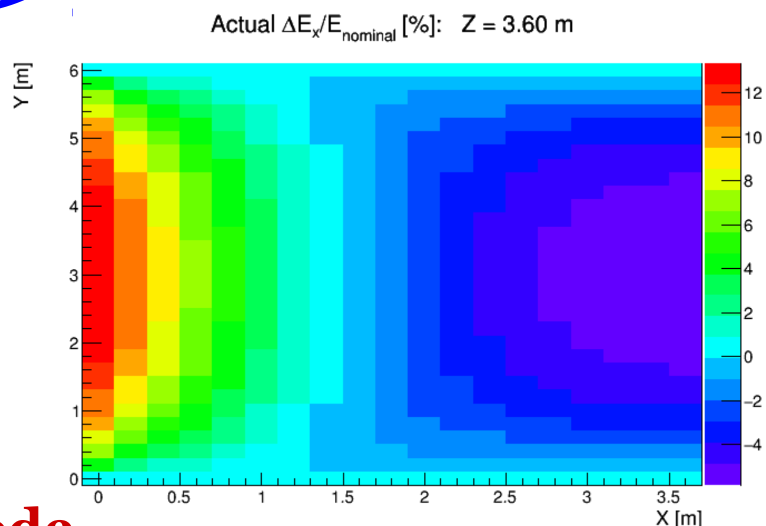
Modified E Field (Central Z)

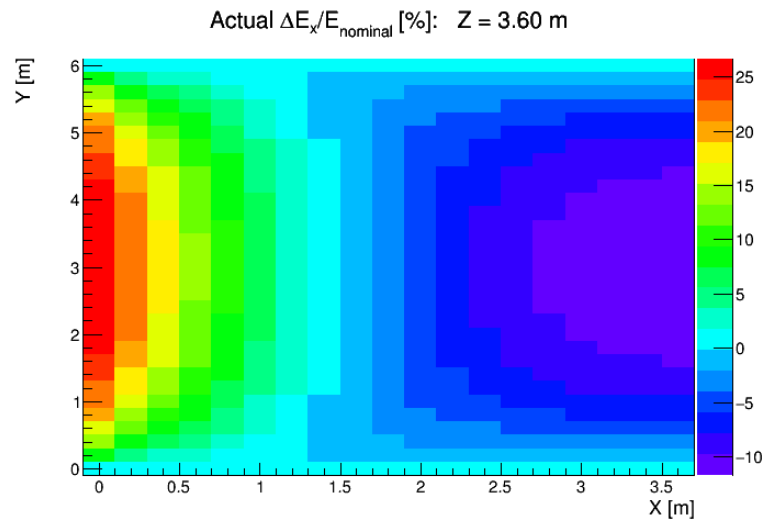
Nominal Geometry

$E_{nominal}$ = 500 V/cm

$E_{nominal}$ = 250 V/cm

E_X

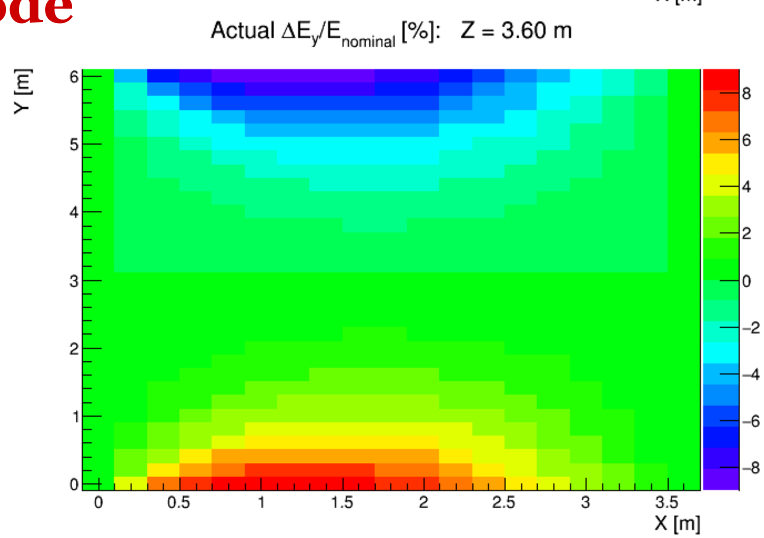


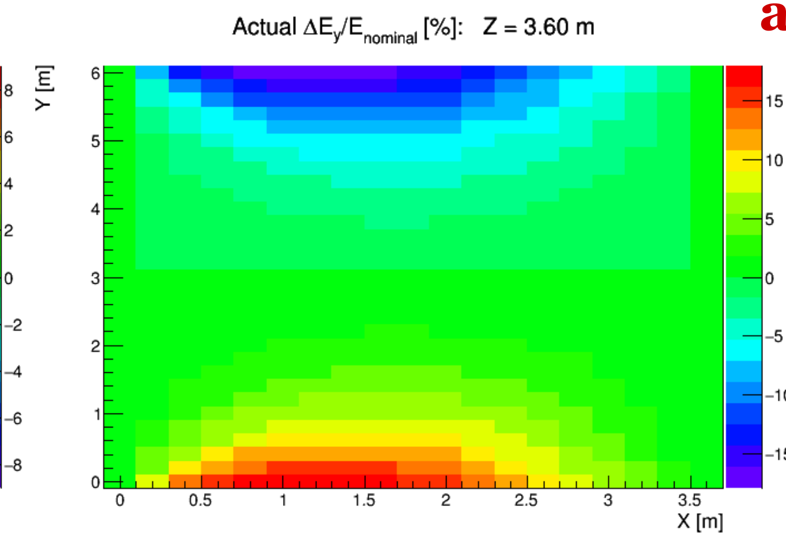


cathode

anode

E_Y





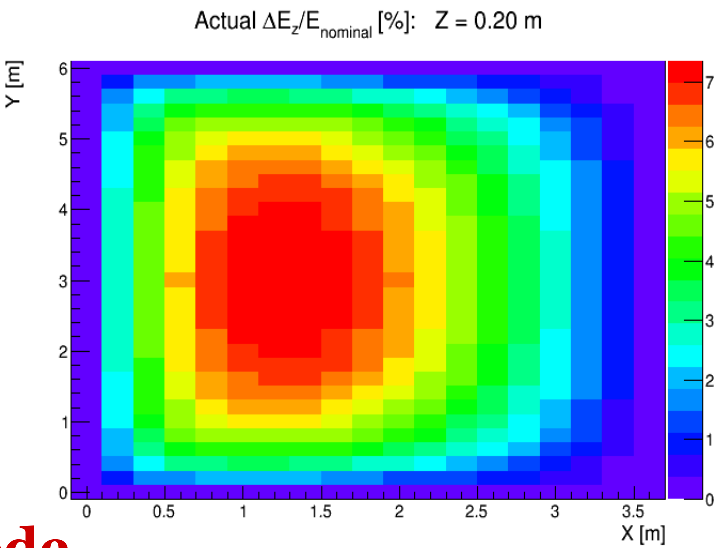
Modified E Field (TPC End)

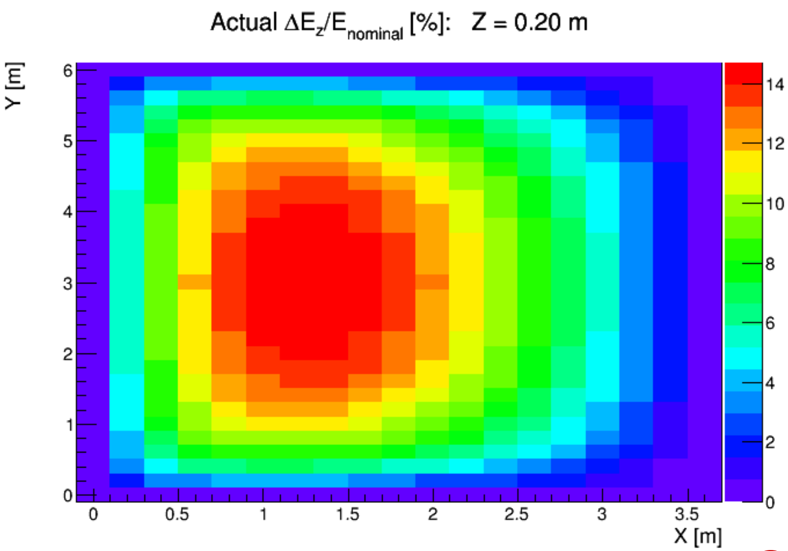
Nominal Geometry

$E_{nominal}$ = 500 V/cm

$E_{nominal}$ = 250 V/cm

E_Z





cathode

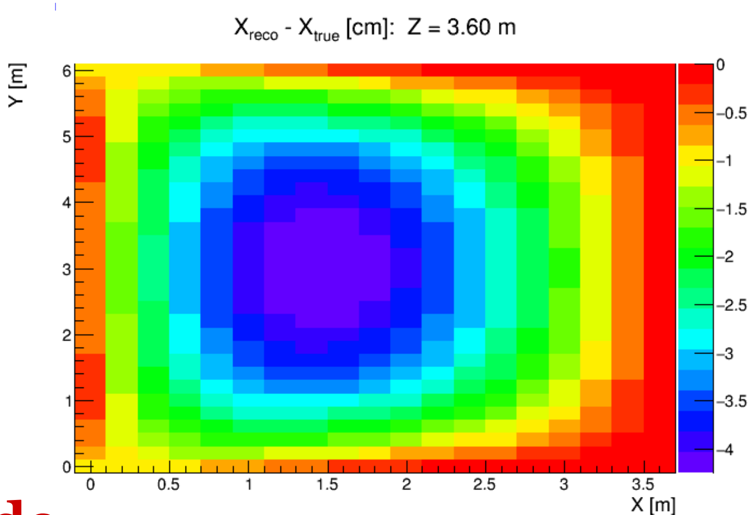
anode

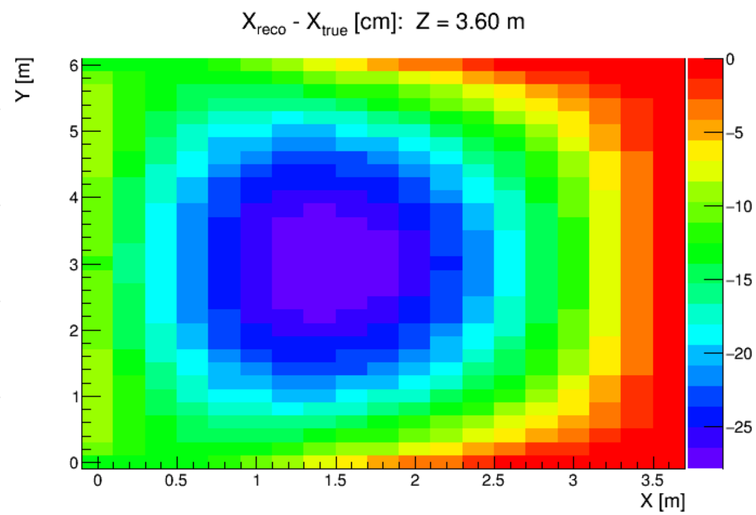
Distortions (Central Z)

Nominal Geometry

$E_{nominal}$ = 500 V/cm **$E_{nominal}$ = 250 V/cm**

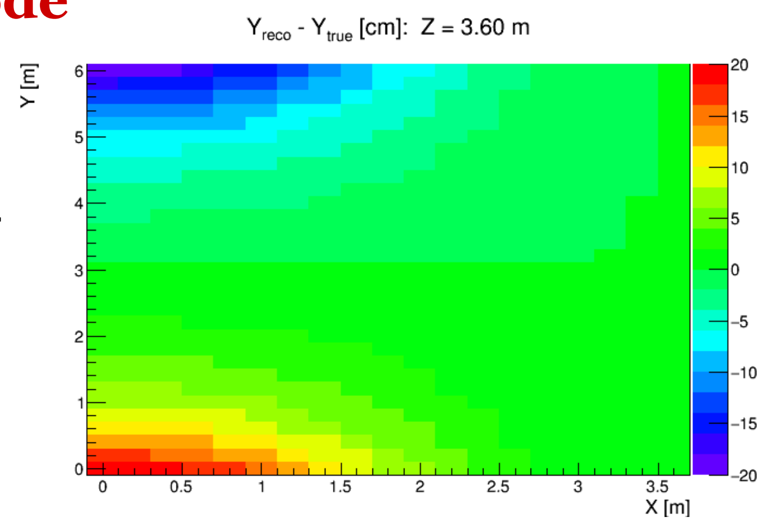
ΔX

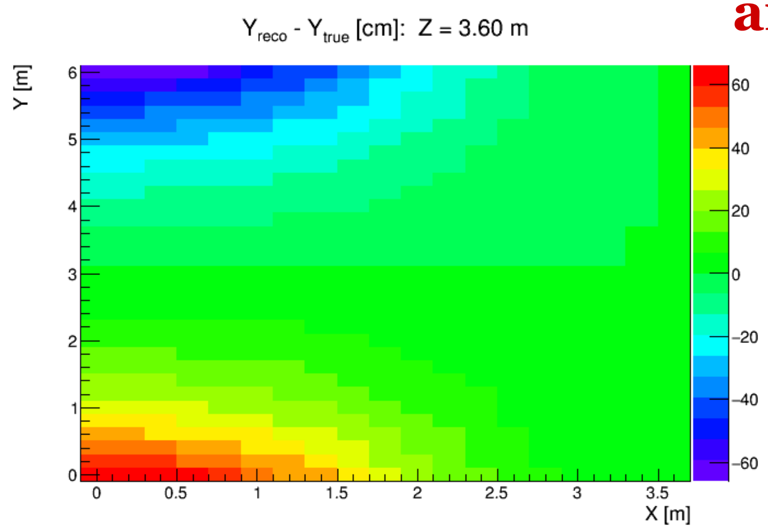




cathode **anode**

ΔY





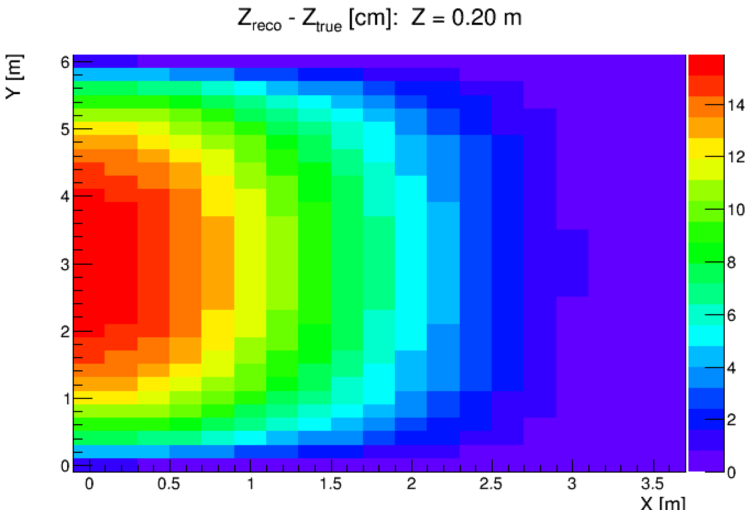
Distortions (TPC End)

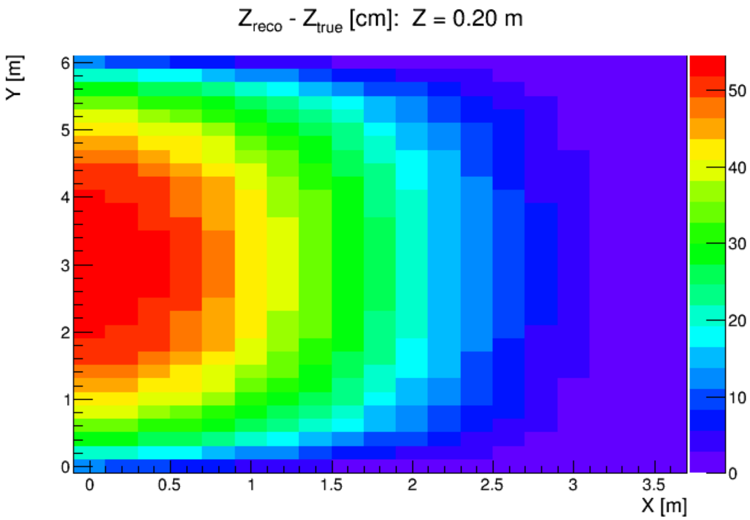
Nominal Geometry

$E_{nominal}$ = 500 V/cm

$E_{nominal}$ = 250 V/cm

ΔZ

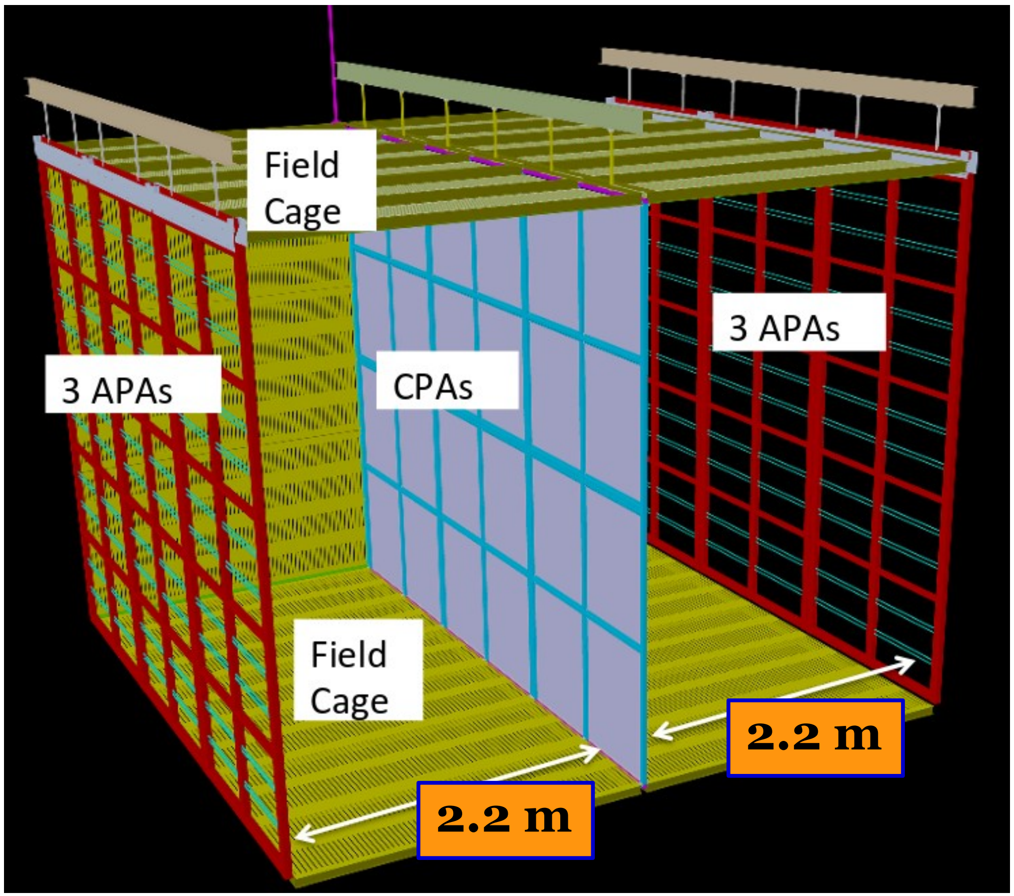




cathode

anode

Modified Geometry



- Modified ProtoDUNE geometry:
  - **Drift (X): 2.2 m**
  - Height (Y): 5.9 m
  - Length (Z): 7.0 m
- Dimensions used for simulations slightly different (to simplify calculations):
  - **Drift (X): 2.4 m**
  - Height (Y): 6.0 m
  - Length (Z): 7.2 m

Modified E Field (Central Z)

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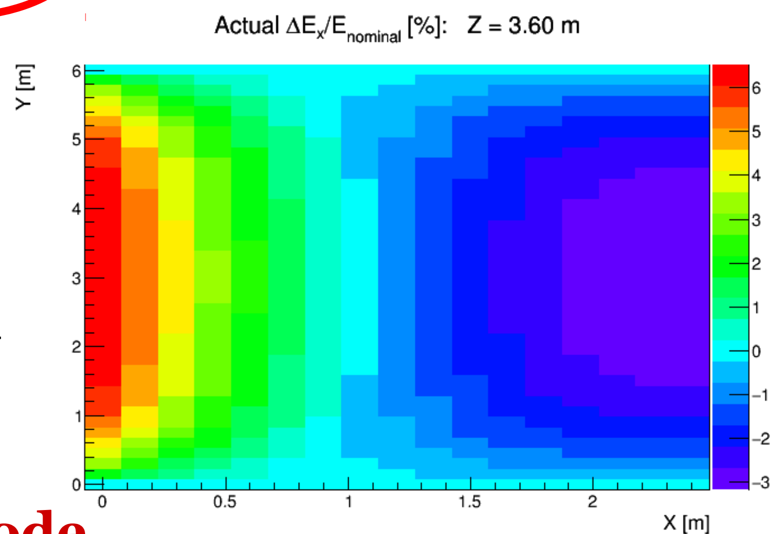
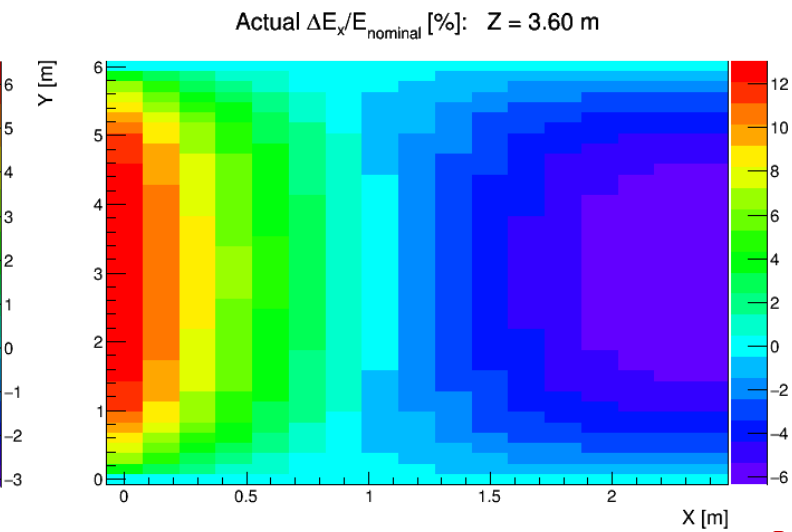
Modified Geometry

$E_{nominal}$ = 500 V/cm

$E_{nominal}$ = 250 V/cm

E_X

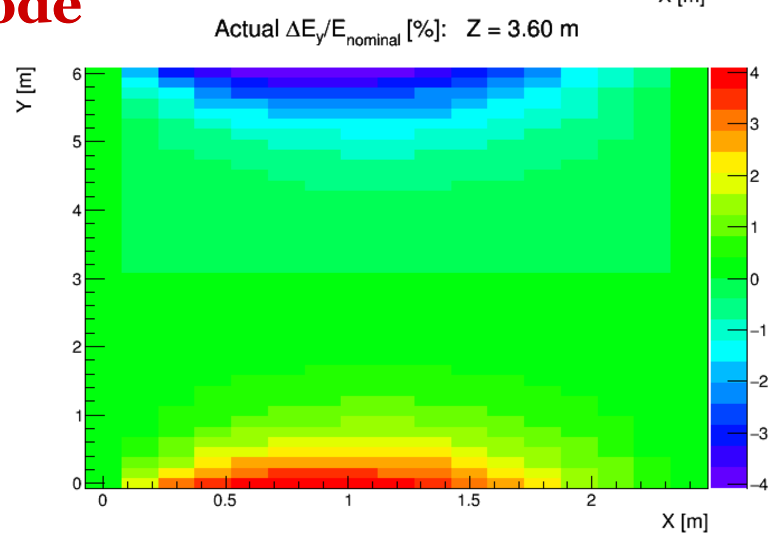


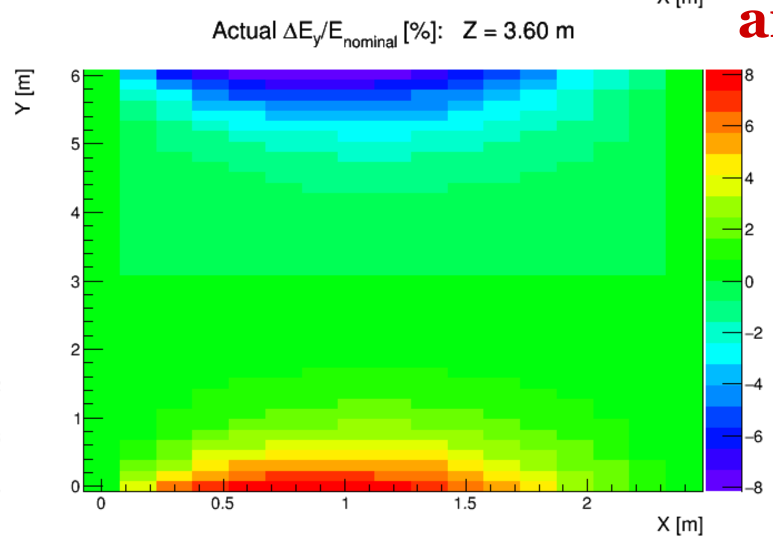


cathode

anode

E_Y





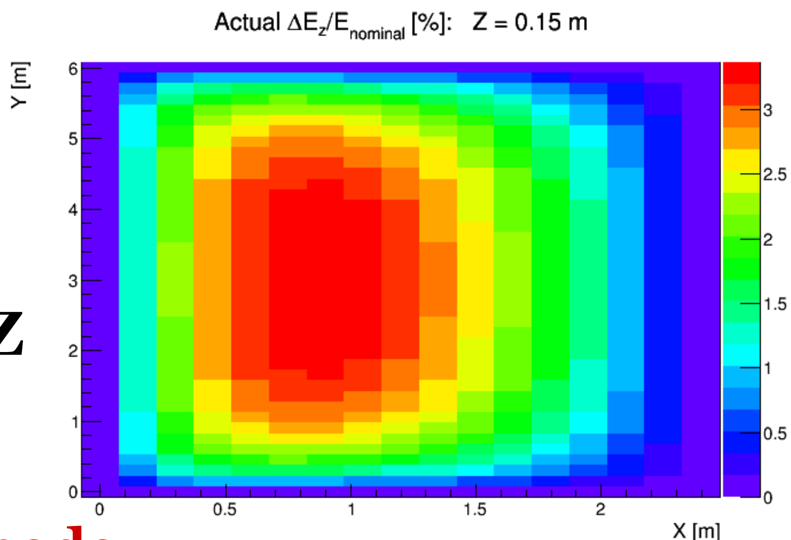
Modified E Field (TPC End)

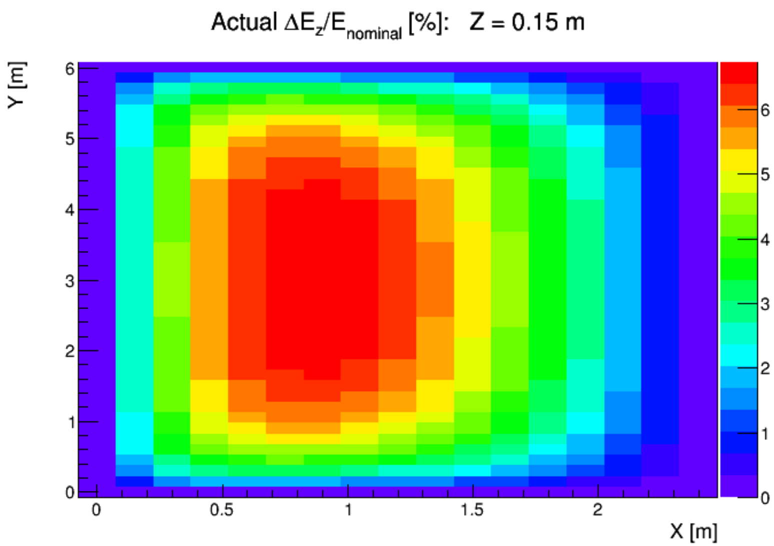
Modified Geometry

$E_{nominal}$ = 500 V/cm

$E_{nominal}$ = 250 V/cm

E_Z





cathode

anode

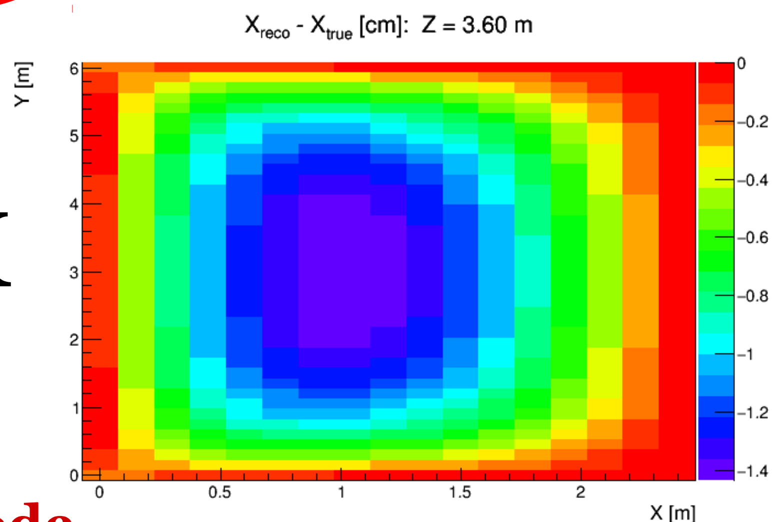
Distortions (Central Z)

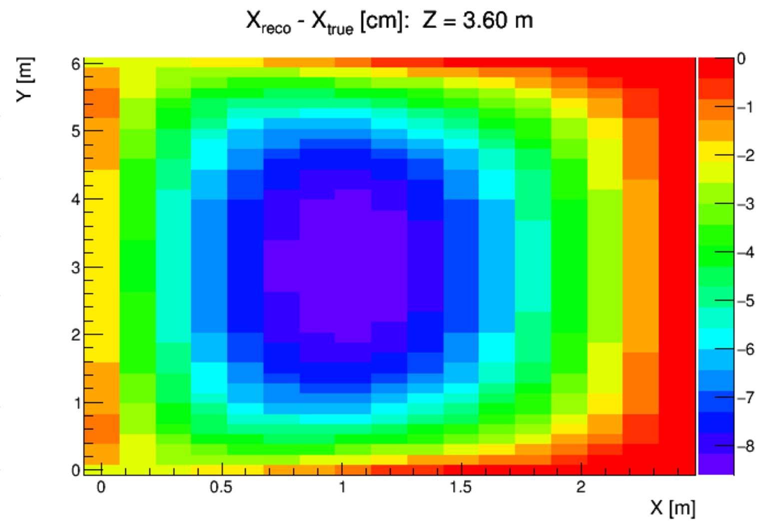
Modified Geometry

$E_{nominal}$ = 500 V/cm

$E_{nominal}$ = 250 V/cm

ΔX





cathode

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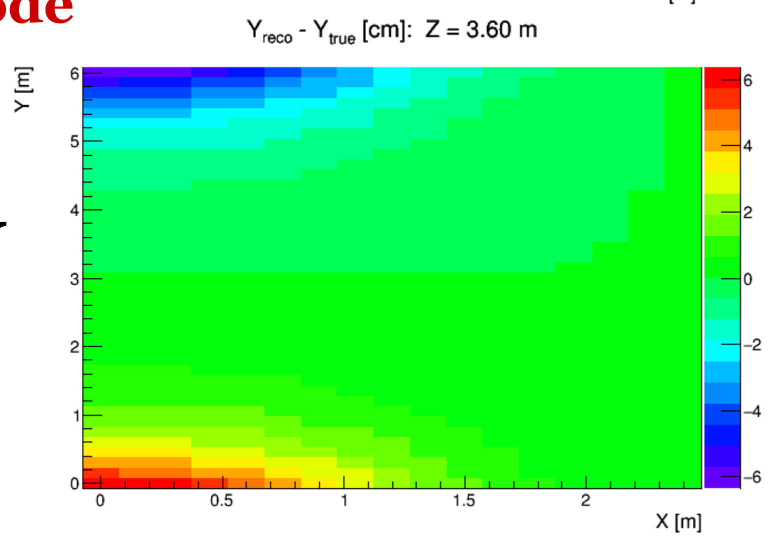
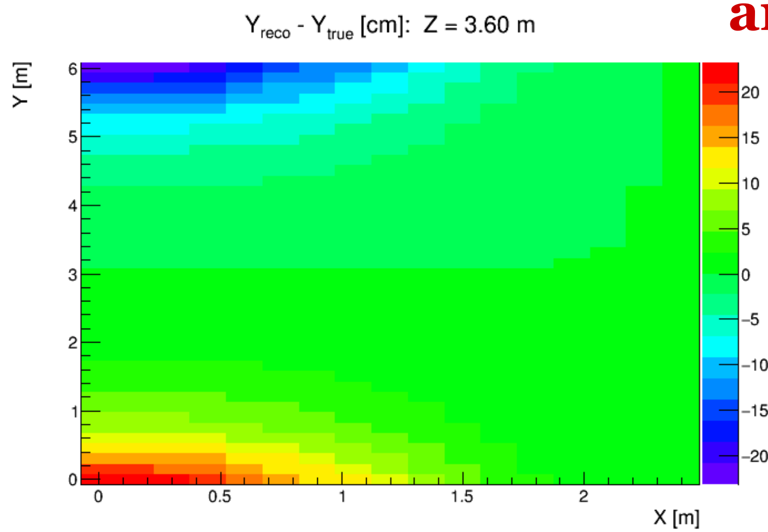
ΔY





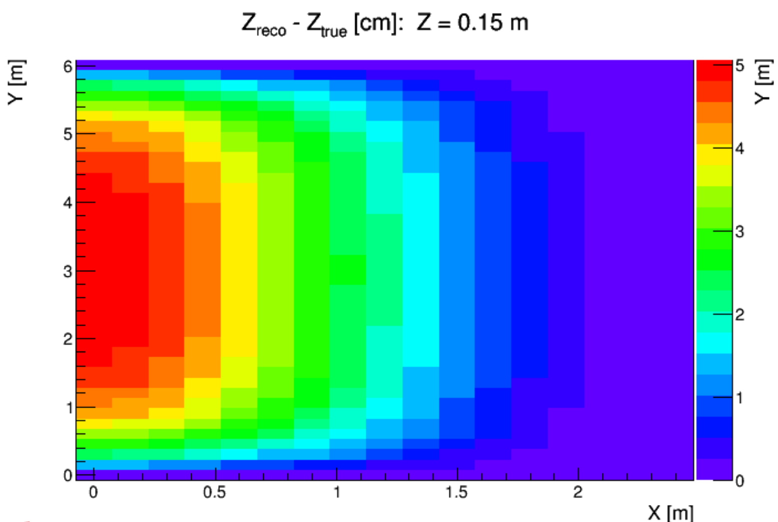
Distortions (TPC End)

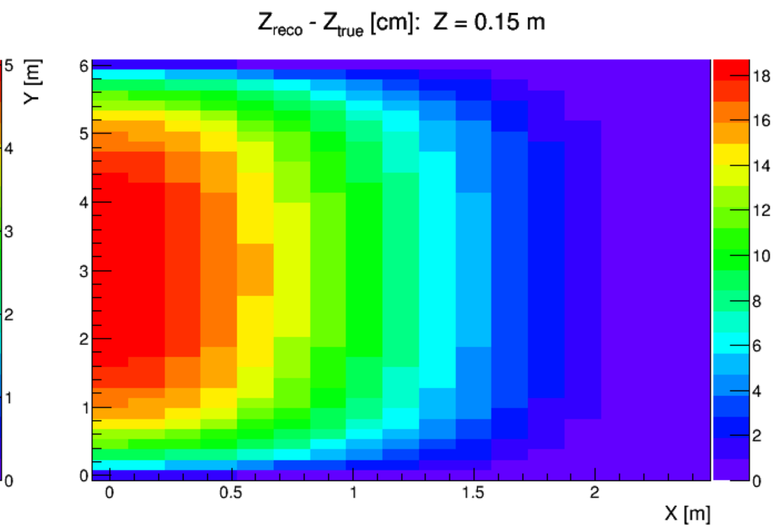
Modified Geometry

$E_{nominal}$ = 500 V/cm

$E_{nominal}$ = 250 V/cm

ΔZ





cathode

anode

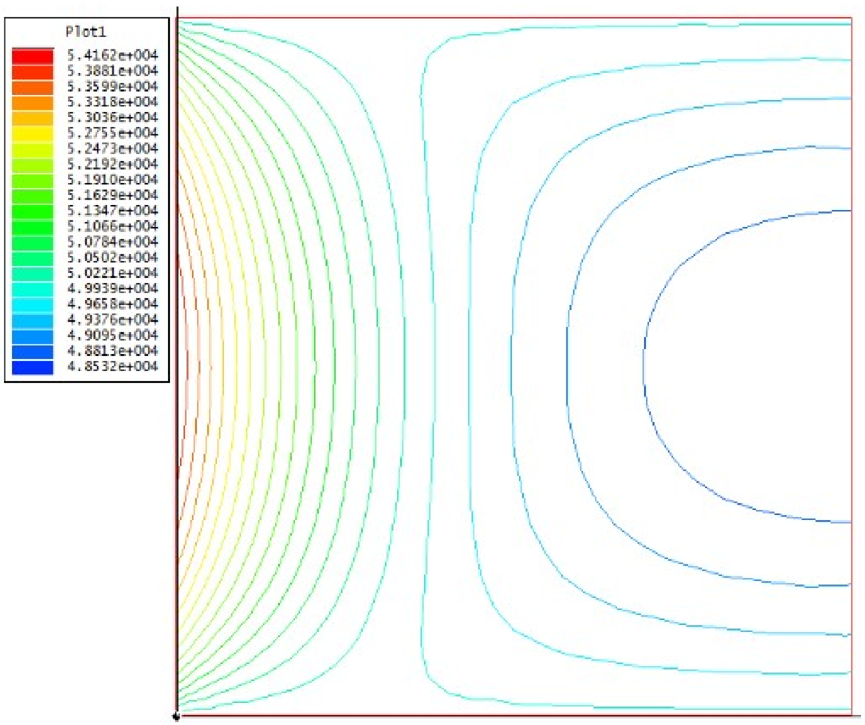
Summary

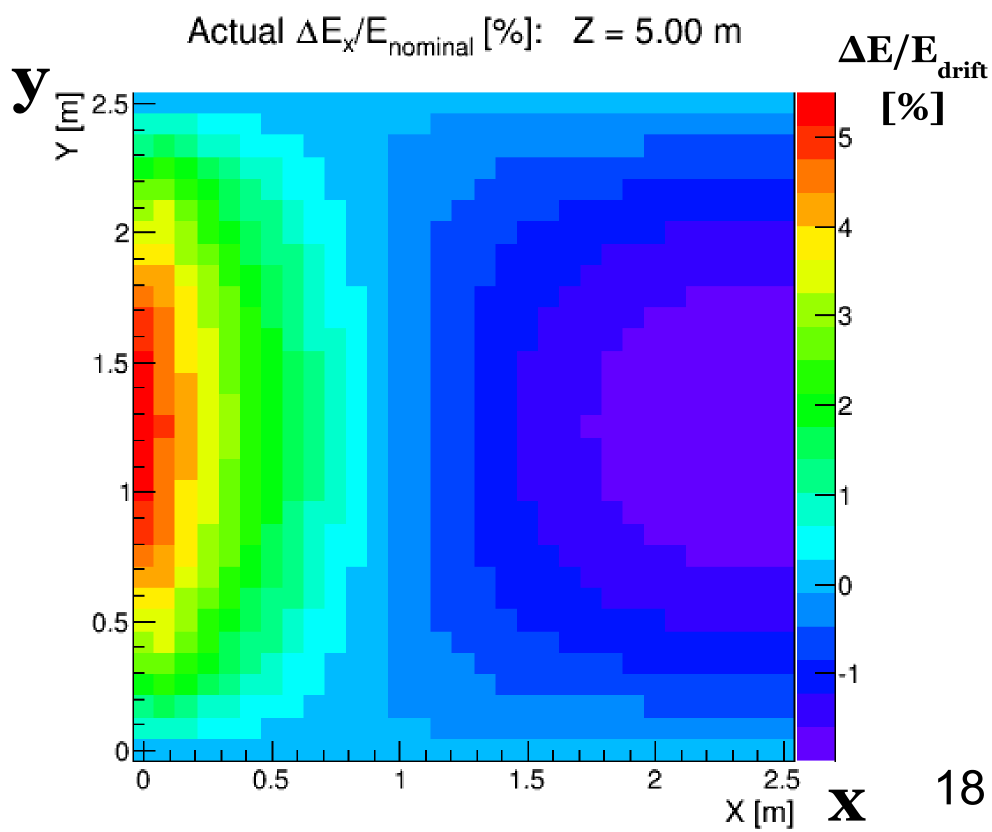
- **SpaCE** – use to study space charge effect and produce SCE distortions throughout a TPC
  - Stand-alone C++ code with ROOT/ALGLIB libraries
- Have also created LArSoft module to store SCE offsets throughout TPC active volume
  - First created to be used for MicroBooNE – currently undergoing modifications to be more flexible for generic LArTPC experiment (including ProtoDUNE)
- Distortions at ProtoDUNE for **nominal geometry** are quite severe! Much larger than those at MicroBooNE (~5 x)
  - **500 V/cm** drift field: **~5 cm** longitudinal, **~25 cm** transverse
  - **250 V/cm** drift field: **~20 cm** longitudinal, **~60 cm** transverse
- Distortions at ProtoDUNE for **modified geometry** (reduced drift length) are much less bad – very similar to those at MicroBooNE (~1.5 x)
  - **500 V/cm** drift field: **~1.5 cm** longitudinal, **~10 cm** transverse
  - **250 V/cm** drift field: **~4 cm** longitudinal, **~20 cm** transverse

BACKUP SLIDES

Compare to FE Results: E_x

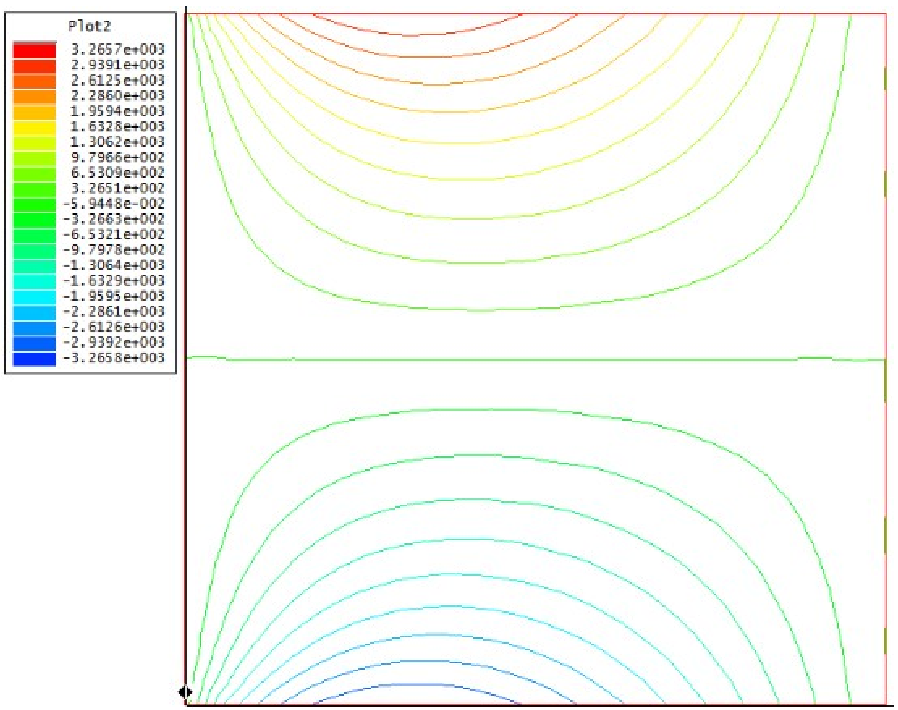
- Looking at central z slice (z = 5 m) in x-y plane (**MicroBooNE**)
- Very good shape agreement compared to Bo Yu's 2D FE (Finite Element) studies
- Normalization differences understood (using different rate)

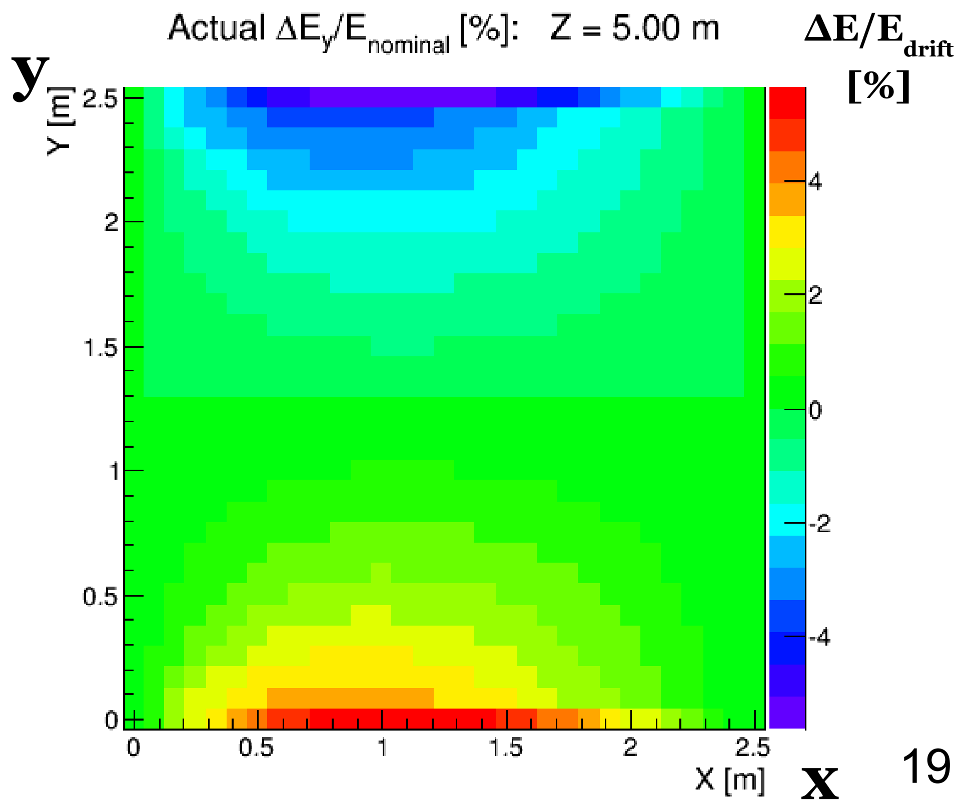




Compare to FE Results: E_y

- Looking at central z slice (z = 5 m) in x-y plane (**MicroBooNE**)
- Very good shape agreement here as well
    - Parity flip due to difference in definition of coordinate system

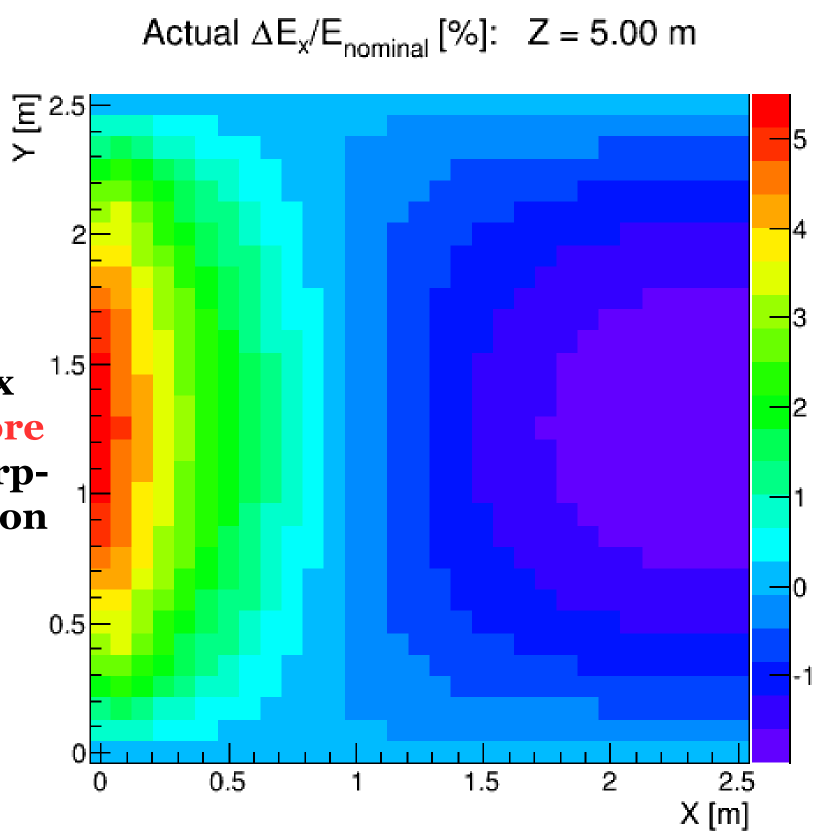


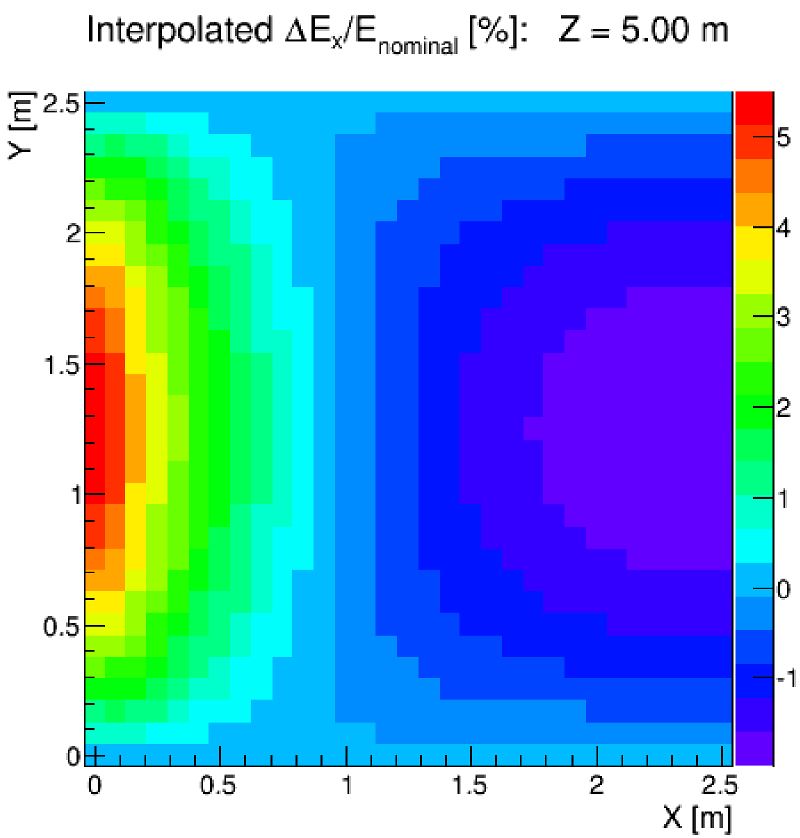


E Field Interpolation

- Compare 30 x 30 x 120 field calculation (left) to 15 x 15 x 60 field calculation with interpolation (right) – for **MicroBooNE**
- Include analytical continuation of solution points **beyond** boundaries in model – improves performance near edges

E_x
Before Interp-olation



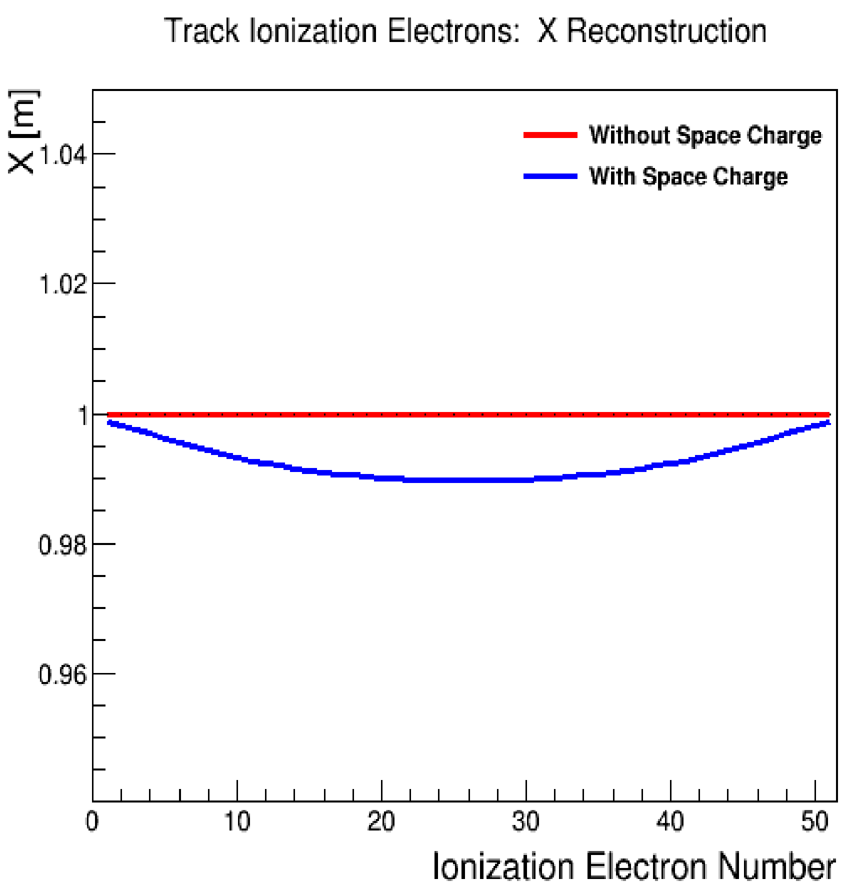


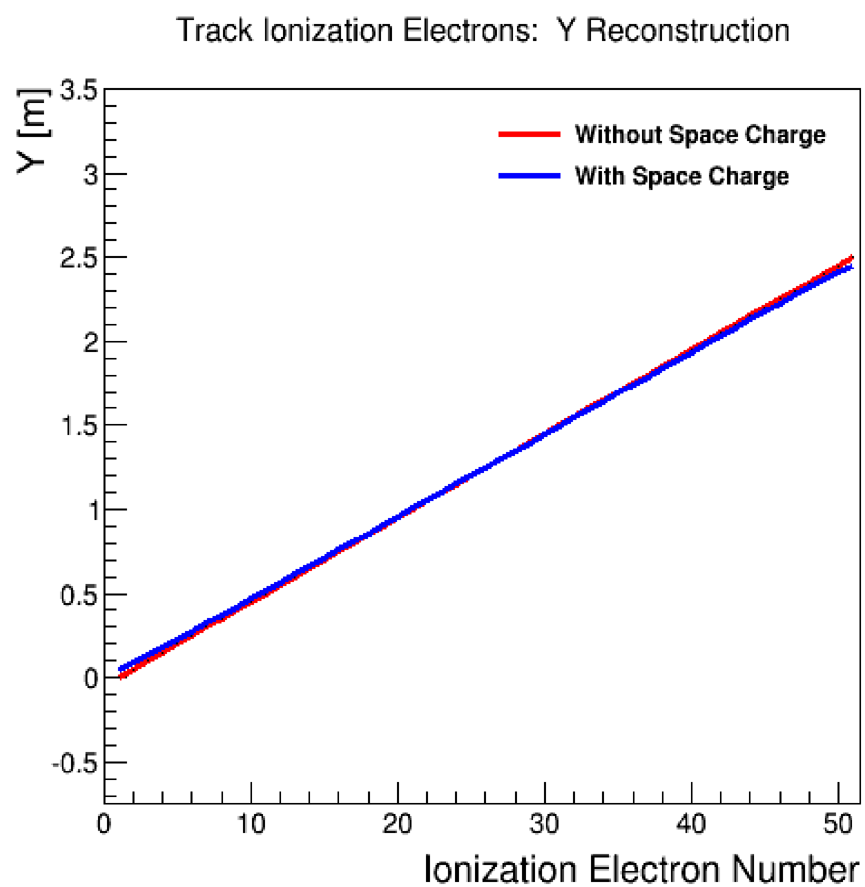
E_x
After Interp-olation

Ray-Tracing

- Example: track placed at **x = 1 m** (anode at x = 2.5 m)
  - z = 5 m, y = [0,2.5] m

MicroBooNE



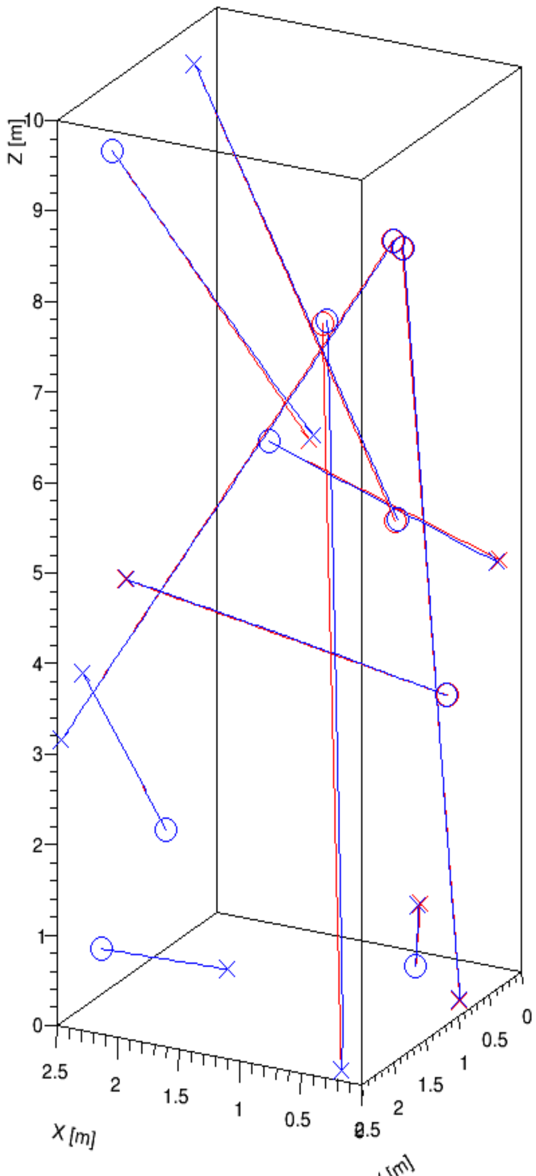


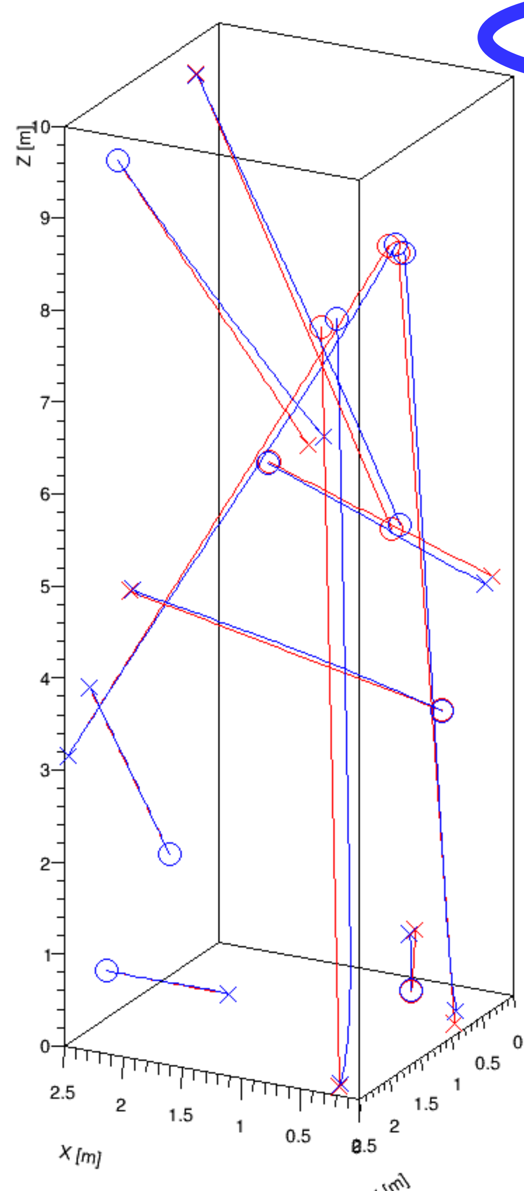
Sample "Cosmic Event"

MicroBooNE

Nominal Drift Field

500 V/cm



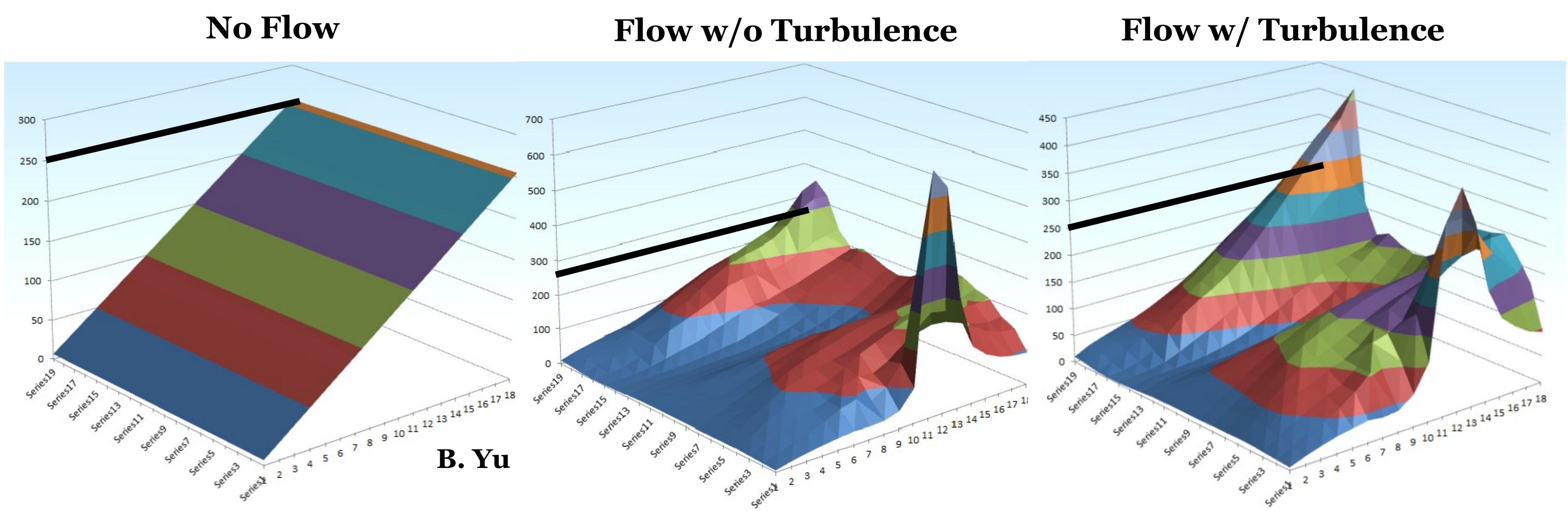


Half Drift Field

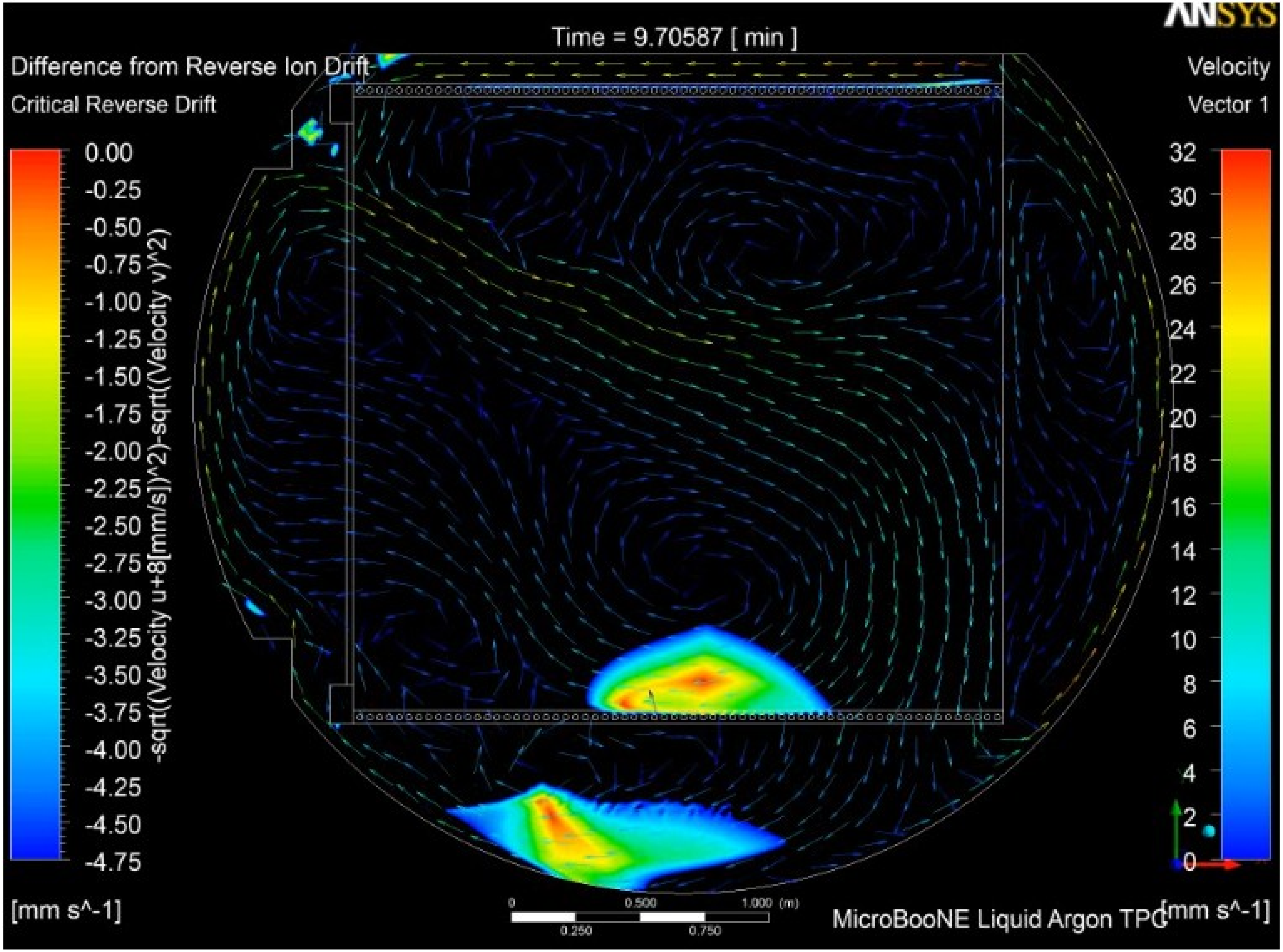
250 V/cm

Complications

- Not accounting for non-uniform charge deposition rate in detector → significant modification?
- Flow of liquid argon → likely significant effect!
  - Previous flow studies in 2D… differences in 3D?
  - Time dependencies?



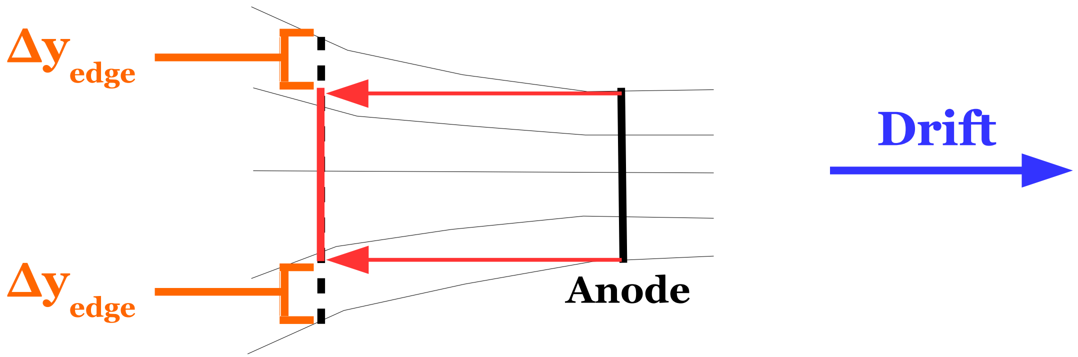
Liquid Argon Flow



B. Yu

Smoking-gun Test for SCE

- Can use cosmic muon tracks for calibration
  - Possibly sample smaller time scales more relevant for a particular neutrino-crossing time slice
  - Minimally: data-driven cross-check against laser system calibration
- **Smoking-gun test**: see lateral charge displacement at track ends of non-contained cosmic muons → space charge effect!
  - No timing offset at transverse detector faces (no E_x distortions)
  - Most obvious feature of space charge effect

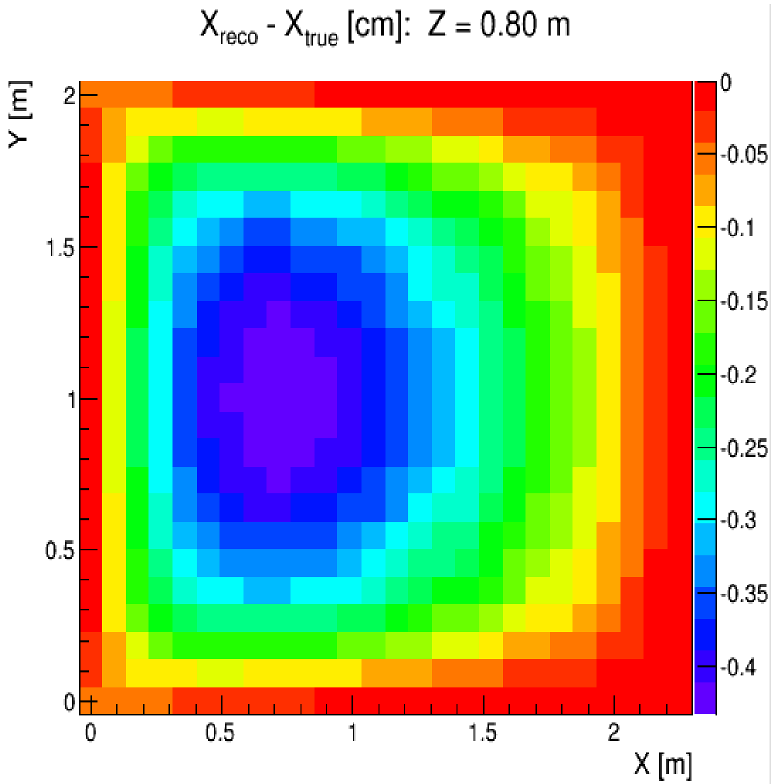


35-ton with LAr Flow

central z slice

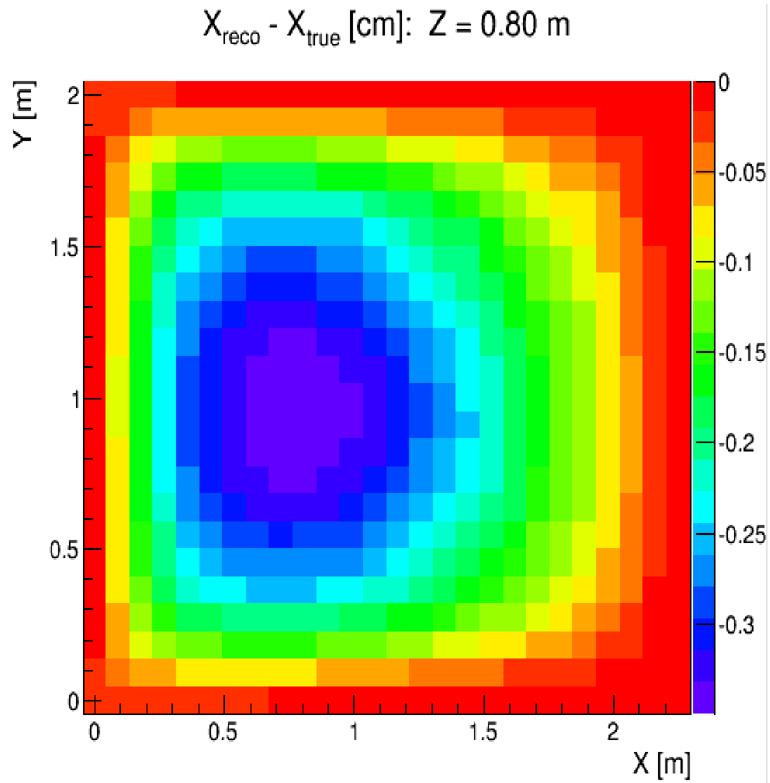
Δx

Without LAr Flow



Δx

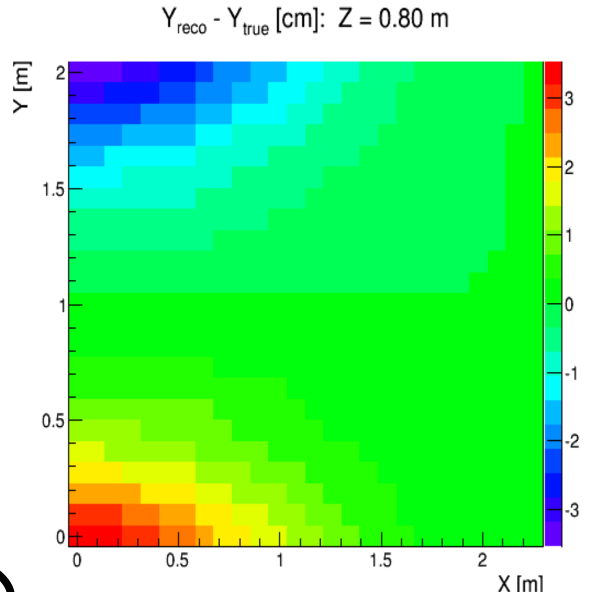
With LAr Flow

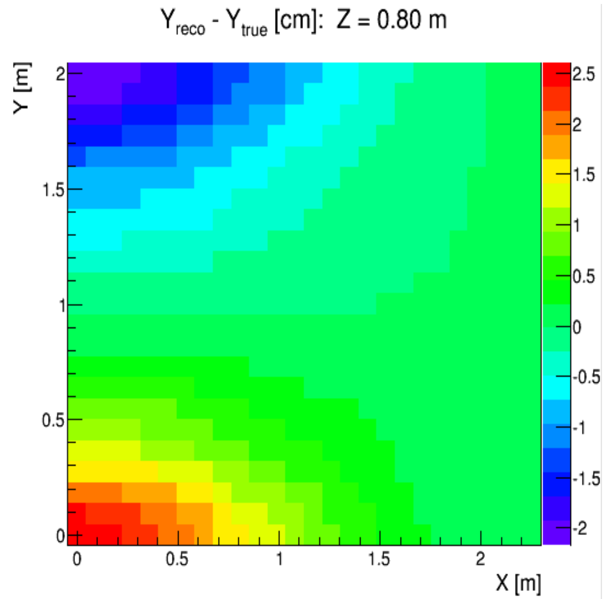


Q map from E. Voirin

35-ton with LAr Flow (cont.)

Δy
Without
LAr Flow



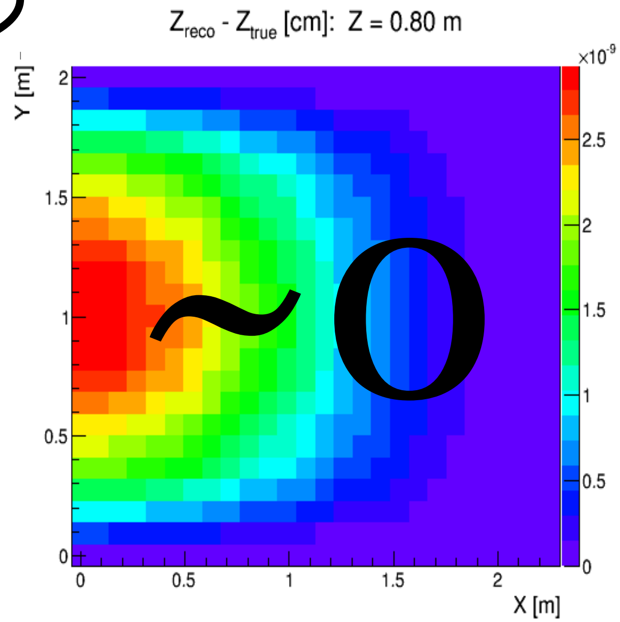


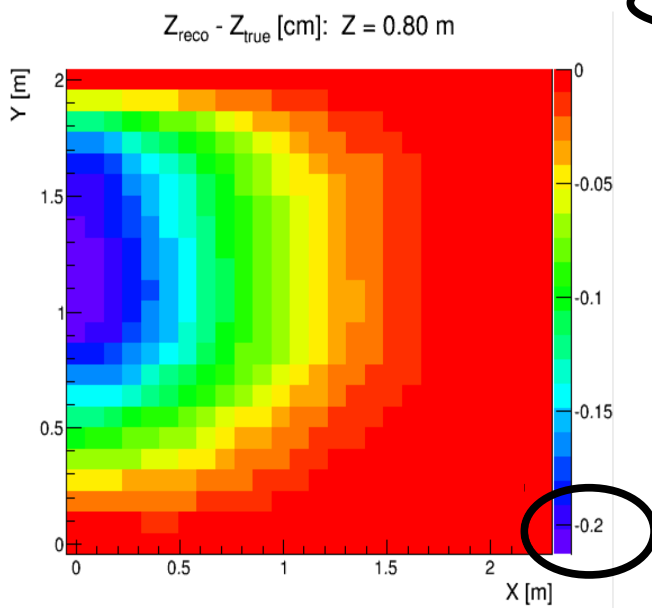
Δy
With
LAr Flow

Q map from E. Voirin

central z slice

Δz
Without
LAr Flow





Δz
With
LAr Flow

Simulation of SC Effect

- Can use SpaCE to produce displacement maps
  - **Forward transportation**: $\{x, y, z\}_{\mathbf{true}} \rightarrow \{x, y, z\}_{\mathbf{sim}}$
    - Use to **simulate** effect in MC
    - Uncertainties describe accuracy of simulation
  - **Backward transportation**: $\{x, y, z\}_{\mathbf{reco}} \rightarrow \{x, y, z\}_{\mathbf{true}}$
    - Derive from **calibration** and use in data or MC to correct reconstruction bias
    - Uncertainties describe remainder systematic after bias-correction
- Two principal methods to encode displacement maps:
  - **Matrix representation** – more generic/flexible
  - **Parametric** representation (for now, $5^{th}/7^{th}$ order polynomials) – fewer parameters
    - Uses matrix representation as input → **use for LArSoft implementation**